A Microscopic View of Parton k_T Effects In High p_T Processes

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Abstract

A microscopic mechanism is proposed for understanding the rather large k_T effects ($< k_T > = 1 - 1.5 GeV/c$, as yet unaccounted for by hard QCD), found by the Fermilab E706 Collaboration for 530 and 800 GeV/c protons incident on light nuclear targets (mass A) like Be. The essential idea is that such high incident projectile momenta tend to break up the confinement barriers for the quark-partons residing in the individual nucleonic constituents of the target nucleus that fall in a tube-like zone around the projectile's path, so that these particles tend to behave as a collection of quark-partons confronting the beam. Using simple combinatorial principles, the resultant $< k_T >^2$ value works out as $(3A_{eff} - 1)\beta^2$, where A_{eff} is the number of affected nucleons in the tube-like zone, and β is a scale parameter derived from the basic quark-pair interaction. Using the previously found results of a Bethe-Salpeter model (attuned to $q\bar{q}$ and qqq spectroscopy), one in which a key ingredient is the infrared part of the gluon propagator, giving $\beta^2 = 0.068 GeV^2$, the desired $< k_T >$ range is reproduced, suggesting the persistence of $soft$ QCD effects even at high p_T.

Keywords: Direct photon; high-p_T reaction; parton k_T distribution; soft-QCD effect.

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1 Brief Background

Direct (prompt) photon production at high p_T inclusive processes is regarded as a valuable tool for extracting the gluon content $G(x)$ [1] of hadrons, due to its sensitivity to the basic Compton process $qg \to q\gamma$, involving point-like photon-quark coupling. This tool is believed to extend the range of x-values beyond the (limited) $x < 0.25$ [2] found from other data. The main theoretical ingredients for such analysis are perturbative QCD for the elementary quark-level process on the one hand, and a model for the inclusion of the nuclear effects on the other. Either of these methods has had a long history, dating back to the Seventies. In particular, the inclusive cross sections for single high-p_T particles produced in hadron-nucleus scattering have long been known to show an 'anomalous' nuclear dependence growing like A^α, where the value of α is itself a function of p_T [3,4]. This "Cronin effect" [3] is believed to be due to multiple (mostly double) scattering effects, which tend to increase the value of α beyond unity (linear dependence).

The other, more natural ingredient, viz., perturbative QCD, has itself been stretched to a considerable extent for an understanding of the anomalous nuclear enhancement, by extending the same to include higher twist effects [5]. More fancy corrections include soft gluon resummation [6]; factorization and soft gluon divergences [7]; such issues and related ones have been discussed in the literature [8]. Yet the existence of sharp deviations between the measured inclusive direct photon production cross-sections and the predictions of perturbative QCD (pQCD), even after the inclusion of next to-leading order (NLO) effects, seems to betray some chinks [9] in the theoretical armour [10]. To examine this problem in more detail, the E706 Group employed their high statistics samples of hard scattering data on inclusive π^0 and direct-photon production cross sections with large p_T values, using beams of 530 and 800 GeV/c protons, as well as 515 GeV/c pions, incident on a Be target (A=9) [11], and compared them with the predictions of NLO pQCD [9-10]. Their results indicate, in company with other related investigations [12,13], that the interacting quark-partons carry significant initial state transverse momentum (k_T), as evidenced from the greatly improved fits to the data [11] after a phenomenological incorporation of these k_T effects in the NLO calculations.

In this brief report, we offer a microscopic mechanism for understanding the rather large k_T effects as inferred from the agreement of the data with the predictions of NLO-pQCD, after smearing the latter with a phenomenological (gaussian) k_T distribution with

$$< k_T >= 1 - 1.5 GeV/c$$

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2 A Microscopic View Of $< k_T >$

The essential idea is the following. At incident projectile momenta as high as $\sim 1TeV/c$, the confinement barriers that keep the quark-partons residing in the individual nucleonic constituents of the target nucleus from mixing with their counterparts from neighbouring nucleons, are torn apart in a tube-like zone around the projectile's path, so that all the nucleons within this zone tend to behave like a collection of $3A_{eff}$ quark-partons, where A_{eff} is the number of nucleons falling with this zone. To estimate A_{eff}, note that if the nucleus is sufficiently small (say $A \leq 10$), almost all the constituents will lie within

this zone, so that $A_{eff} = A$ in this case. On the other hand, if the nucleus is rather big, then many nucleons will be outside the path of the projectile, and hence largely unaffected by the encounter. One therefore expects a more or less sharp cut-off value of A beyond which the size of the nucleus will hardly matter. While a precise estimate of A_{eff} depends on the radius of the tube surrounding the projectile's path, and is a difficult geometrical/dynamical problem, a working value is $A_{eff} \approx 10$ which will be adopted for the calculation to follow. This is perhaps an oversimplified description of the scenario, but hopefully captures the essential flavour of the basic mechanism: A huge proliferation in the number of scattering centers from the nucleonic to the quark-partonic level greatly enhances the scope for the transverse momentum distribution in the initial nucleus to influence the inclusive scattering process, albeit within the constraints of $A \leq A_{eff}$. This is a feature which the NLO pQCD theory [10] seems unable to capture. Ignoring double scattering effects [3-4], which are presumably small, the mechanism is nevertheless expected to depend on the incident energy per nucleon, so that a higher mass number (A) would need a proportionately larger energy to penetrate the confinement barriers in the constituent nucleons, but an incident momentum as high as $> 500 GeV/c$ is probably high enough to pulverize the nucleons lying within the projectile's path. As will be shown below, with the use of simple combinatorial principles, the resultant $< k_T >^2$ value works out as $(3A_{eff} - 1)\beta^2$, where β is a scale parameter incorporating the basic (gluonic) interaction of the quark pairs.

2.1 A Non-perturbative Estimate of β^2

Since an estimate of β is as yet inaccessible to pQCD, it calls for a resort to the non-perturbative QCD regime on which unfortunately no consensus exists on the calculational techniques, necessitating a certain amount of model building. To minimise the uncertainties of the model, its key parameters must be subjected to several crucial tests bearing on its predictions as a prior check on its reliability. The model we have chosen to employ is based on a QCD-motivated Bethe-Salpeter equation [14-17] in which the key ingredient is the gluon propagator [14] whose infrared part incorporates confinement, and thus represents the soft-QCD regime. It is calibrated to both $q\bar{q}$ and qqq spectroscopy [15], as well as to the hadron form factors [17] within a common dynamical framework, and makes a definitive prediction for β^2 which controls the quark-parton distribution in a non-strange baryon with the value $\beta^2 = 0.068 GeV^2$ [15b, 17b]. This is the input we propose to take as a means of accounting for the high $< k_T >$ value needed for the process under study [11], but its mode of derivation does not concern us here, and may be found in the cited references [14-17].

2.2 Derivation of $< k_T >^2 = (3A_{eff} - 1)\beta^2$

To fix our ideas on the essential steps of the calculations, we start with the quark-parton distribution in the proton wherein the two normalized internal Jacobi variables (ξ, η) are [16]

$$\sqrt{3}\xi = p_1 - p_2; \quad 3\eta_{=} - 2p_3 + p_i + p_2 \tag{1}$$

which can be further broken up into longitudinal $(\xi, \eta)_{\parallel}$ and transverse $(\xi, \eta)_{\perp}$ components. Being interested in the transverse part of the distribution here [18], we concentrate only

on

$$\rho_\perp = N_\perp \exp\left[-\xi_\perp^2 - \eta_\perp^2\right]/\beta^2 \tag{2}$$

where $N_\perp$ is the normalization attuned to $\int \rho_\perp = 1$. The mean square transverse momentum for the quark-parton distribution may now be defined as

$$< \xi_\perp^2 + \eta_\perp^2 >= \int d^2\xi_\perp d^2\eta_\perp (\xi_\perp^2 + \eta_\perp^2)\rho_\perp \tag{3}$$

which works out simply to $2\beta^2$. Its square root which may be identified as $< k_T > = \sqrt{2}\beta$ $= 0.37 GeV/c$, is unfortunately too small to account for the observed value in Be [5], but now we are to take account of the mass number (A_{eff}) effect.

Now the transverse degrees of freedom in a nucleus with $3A$ quark-partons are $2 \times (3A_{eff} - 1)$, (after subtracting unity for the overall c.m. motion). This gives the initial transverse quark-parton momentum distribution as

$$\rho(\xi_{i\perp}) = N_\perp \exp\left[-\sum_{i-1}^{3A-1} \xi_{i\perp}^2\right]/\beta^2 \tag{4}$$

where the normalization constant is constrained by

$$\int \Pi_{i=1}^{3A_{eff}-1} d^2\xi_\perp \rho(\xi_{i\perp}) = 1 \tag{5}$$

The mean square transverse momentum now works out as

$$\begin{aligned} < k_T >^2 &= < \sum_{i=1}^{3A_{eff}-1} \xi_{i\perp}^2 > \qquad (6) \\ &= \int \Pi_{i=1}^{3A_{eff}-1} d^2\xi_\perp \left(\sum_{i=1}^{3A_{eff}-1} \xi_{i\perp}^2 \right) \rho(\xi_{i\perp}) \\ &= (3A_{eff} - 1)\beta^2 \end{aligned}$$

Substitution of $\beta^2 = 0.068 GeV^2$ [15b,17b] gives for $A_{eff} = 9$ [11] the value $< k_T > = 1.33 GeV/c$, which is well within the range of values considered by the E706 Group [11].

3 Resume And Discussion

We have tried to offer a microscopic description of k_T effects in the rather specific context of direct-photon production in proton-Be collisions found by the E706 Group [11]. The assumption underlying the description is that the basic scale of the transverse quark-parton distribution is the same as that obtaining in a qqq hadron (proton). And *this* in turn is determined by the parameters of the *infrared* part of the gluon propagator mediating the quark-pair interaction in the non-perturbative QCD regime, a logic which points to effects beyond the NLO pQCD scenario [10]. The other aspect of the assumption concerns the A-dependence of the effect which comes about from the fact that at sufficiently high incident momenta the projectile is able to "see" the quark constituents that come in the immediate zone surrounding the path of the projectile through the nucleus, and this greatly enhances the source of the k_T distribution to almost three times that of the number of "effective" nucleons.

Table I: Major Expts on Direct Photon Production
k_T values for various targets

Expt	Beam, Target	k_T expt(GeV/c)	k_T theory (GeV/c)
E-706 [11]	p , H	0.7	0.52
E-706 [11]	p , Be	1.2-1.4	1.32
E-629 [22]	p , C		1.54

Table I gives a list of major experiments on various targets, together with the k_T-values which fit the data, including the corresponding values according to the proposed mechanism. For sufficiently small A, our formula seems to account for the observed value of $< k_T >$ needed to understand the Be data [11] for which the full A value is hopefully operative. For pp [19] and $p\bar{p}$ [20] reactions, $A_{eff} \approx 2$, (taking account of the resultant effect of the target and projectile), and the best fit value at $k_T \approx 0.7 GeV/c$ for both [11] is not much different from the value of $0.52 GeV/c$ predicted by our formula which indicates a fairly strong dependence on the A-value. Similar experiments have been carried out for Cu, Be and H by the E-706 group [21]; and for Be, C and Al by the E-629 group [22], but no clear data on $< k_T >$ are as yet available. Although we expect on the basis of our ansatz that for heavier nuclei like Cu [21] and Al [22], the k_T value should *not* increase proportionately with the mass number, the fuller implications of the ansatz would, in all probability, need several more targets with considerable variations in their A-values, as well as a wider range of incident energies, before the proposed mechanism can claim a proper test.

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